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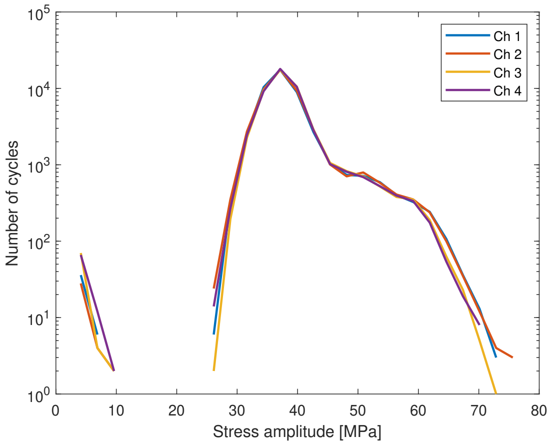

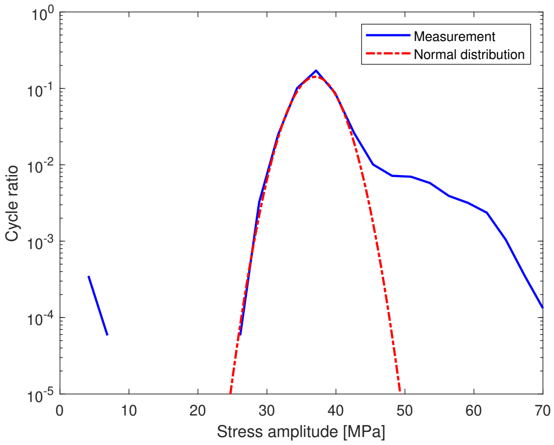

Influence of track status on vehicle on-board measurements

Master’s thesis in Mobility Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025
www.chalmers.se

Master's thesis 2025

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Cover: Stress spectra and a fitted normal distribution, forming the basis of the model used in this study.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2025

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Abstract

This study sets out to explore a possible correlation between track quality and data collected by onboard measurement systems. With the rise of condition-based maintenance on railway vehicles, onboard measurement systems could be exploited to assess track quality in addition to their original purpose. An SJ X40 train operating revenue traffic creates the foundation for this study.

Onboard measurement data from 2022 have been examined together with track measurements to form a basis for a correlation analysis. Axle strain measurement have been converted into stress spectra which have been analysed using a truncated normal distribution. This in turn was related to track quality data corresponding to the time periods from when the onboard measurements were taken. A possible correlation was explored through linear regression and Pearson's correlation coefficient. The resulting analysis could not establish a correlation between track quality and onboard measurements, however some results indicate that a correlation might exist. Through the same analysis, it was possible to conclude that the influence of track characteristics dominate over track quality in the onboard measurement data, showing the need to filter the onboard measurements when making assessments of track quality.

Keywords: Onboard measurements, condition-based maintenance, track quality, track quality assessment.

Acknowledgements

Firstly, a huge thanks to my examiner Anders Ekberg from Mechanics and Maritime Sciences and my supervisor Michele Maglio from Trafikverket who have always been open to questions and discussions. Together, you have given me the guidance needed to understand what I've been working with and inspired me to dive deep into the subject of data analysis. I have learned a lot of new things doing my thesis, and also experienced that everything does not always end up as you expect. Thanks to Elena Kabo for helpful insights, and I look forward to having you as a supervisor as a PhD student.

Thanks to SJ for allowing me to use your onboard measurements for this study. Your data form the basis for my thesis, which proved to be an interesting journey with many learning opportunities. Furthermore, thanks to Lucchini for guiding me through the usage of the onboard measurement system, and answering my questions and solving any problems that arose.

Eskil Wirdheim, Göteborg, May 2025

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1

Introduction

Onboard telemetry for railway vehicles has become common in monitoring vehicle condition, as well as in estimating component health and maintenance needs. This has allowed the strategy of Condition Based Maintenance to be applied, which can reduce the need for preventative as well as reactive measures [1]. Instead of maintaining parts according to a set time schedule, the condition of parts are monitored, and maintenance is scheduled when set thresholds are expected to be reached. While the main purpose might be monitoring of vehicle condition, a faulty track will also influence the onboard measurement results [2]. This could potentially be exploited for track quality assessment and maintenance planning. This study will explore whether a correlation can be found between onboard measurement data and the track status.

The SmartSet® is a monitoring system that measures wheel axle strains, converting these into stress spectra and location-tagged overload indications [3]. It has been installed on an SJ X40 regional passenger train in revenue traffic. This system has previously been used to analyse wheel and axle health and how load conditions can be assessed and approximated as load spectra [4],[5],[6]. The current project aims to investigate whether these onboard measurements can be connected to track status. If a correlation between axle stress data and track geometry deterioration can be found, the confidence level of track health approximations based on onboard measurement data needs to be determined. Accurate estimations would indicate that there is a possibility of measuring track health through revenue trains and thereby reduce the need for specialized measurement vehicles.

This study will be based on measurements acquired from the Swedish western main line, known as Västra Stambanan. Onboard measurements from different track sections will be compared to Trafikverket's measurements of track status from the systems BIS [7] and Optram [8]. These systems store multiple parameters characterising the track condition of the Swedish railway network. Multiple parameters will be studied, and will form the foundation for a statistical analysis. The paper is structured in the following way: A literature study is first presented. Then, track condition data is presented in chapter 3 and onboard measurement data presented in chapter 4. Analysis of the data with a focus of possible correlation is presented in chapter 5. Lastly, a discussion with concluding remarks is presented in chapters 6 and 7.

2

Literature study

This chapter describes the measurement system that is used together with necessary background information. Track status and its influence on railway vehicles is explored, as well as methods to analyse a possible correlation.

2.1 Onboard measurements

Onboard measurement systems are becoming increasingly popular due to the potential of economic and safety advantages they bring. One main purpose of these systems is to allow for condition based maintenance (CBM), where the idea is to continuously monitor parts to get accurate measurements on when maintenance is needed [9]. The advantages of CBM are that parts are maintained and replaced according to the actual usage of the parts, not according to time intervals where parts may be replaced prematurely or, if conditions are rough, parts are not replaced in time which can lead to failure [4]. This optimizes usage of parts and thus enables lower operational costs and increasing safety. However, onboard measurement systems are not without drawbacks. A review performed by Bernal *et al.* [9] looks at the application of onboard measurement systems on freight trains to make CBM possible, and some challenges of these systems are highlighted. Most systems require a power source and a way of storing or communicating the data recorded, which can be especially challenging for freight train installations. Onboard measurement systems also bring a need to collect and analyse the large amounts of data that the systems generate [10]. Usually, a model of compressing the data into one or a few useful metrics is used to reduce the required capacity for data transfer and storage. On the other hand, data compression might lead to lower accuracy or less nuanced data.

The use of the SmartSet® onboard measurement system has been described in detail by Maglio *et al.* [4]. The measurements were used together with numerical simulations to evaluate the consequences of rolling contact fatigue (RCF) and other forms of wheel tread damage on the wheels of a passenger train. In short, the measurement system is mounted on the leading axle of an SJ X40 train of the model Alstom Coradia Duplex and measures strain at four points around the axle's cross section. These are at 0°, 90°, 225°, and 315°, using the first channel as a reference point at 0°. Since the opposite side of the axle experiences the same bending strain but in the opposite direction, these correspond to strain measurements at 45 degree intervals of the axle. However, shear strains affect the accuracy of this assumption since these will have the same effect on both sides of the axle. Using the wheel axle geometry, the strain measurements are converted into stresses, which are in turn stored in a stress spectra through cumulative rainflow counting. The study in [4] utilizes these measurements to verify simulations done on the effects of wheel out-of-roundness (OOR), shift in contact point due to curves, as well as the effects of rail roughness. It was shown that wheel tread damage had an effect on the measured stress spectra. However, it was also concluded that a shift in contact point can have a larger effect on the measurements, and simulations showed that rough rail can overshadow other effects through a significant increase in axle stresses. Furthermore, a study by Maglio *et al.* [5] uses data from the SmartSet® to estimate the fatigue life of the wheelset, with a focus on the axle. By fitting two truncated normal distributions to the measured stress spectra, a statistical model of fatigue life was derived which showed a strong correlation to the field conditions. One normal distribution represents ordinary loading, the other representing high loads generated in the presence of switches and crossings. This model is possible to use in a CBM approach by predicting the remaining fatigue life.

2.2 Influence of track status

Track condition monitoring is important in railway traffic due to the deterioration of tracks over time. Usually, track recording vehicles are used to assess track quality and record data, and there are multiple factors to account for [11]. Rail deterioration, track irregularities, deviations from nominal track geometry, and deterioration in the sub-grade all have effects on track condition. Ekberg and Kabo [12] presents an extensive review of parameters required for track health monitoring and prediction. It is related to the condition of sub-ballast and ballast, sleepers/slabs and fastening systems, and rail, where each category has multiple parameters required to provide an accurate model of the track condition. These should both be considered on a global level of the track, and on a local level where extreme faults can cause immediate safety issues. However, it is also noted that the operational conditions are important to take into account, where different types of traffic have different requirements on the track.

Based on variations in wheel-rail contact forces, it should be possible to determine track status properties through onboard measurement systems. Wheel-rail contact forces are usually divided into static, quasi-static and dynamic loads. Static loads are due to the weight of the vehicle, quasi-static loads are shifts in the static load due to external factors such as curves, and dynamic loads are time-dependent loads due to, for example, track irregularities, switches, or wheel flats [13]. Meymand et al. [14] show an extensive review of different models of wheel-rail contact, which details how contact forces can be estimated. Track with irregularities can cause higher contact forces, which can be visible through the data of onboard measurement systems [2]. Maglio *et al.* [6] looks at the effects of track condition on the SmartSet® onboard measurement system, which also highlights an additional feature of the system. A stress threshold can be defined for the system, and when a stress above the threshold is registered, a stress history of 5 seconds is saved, centred around the overload. This is stored together with the GPS location where the overload occurred and vehicle speed data. The study utilizes the same truncated normal distributions as discussed in section 2.1, and investigates the effects of different track characteristics. It was found that the existence of more switches and crossings increases the standard deviation for both the distribution representing quasi-static loading and the distribution representing overloads, due to the more frequent occurrence of high loads. Curved track increased the mean value of the normal distribution representing ordinary loading and, if the amount of curves was very high, a potential increase in the standard deviation of the same normal distribution. For track quality, Trafikverket's parameter QS-ratio was used, which is a general measurement of track quality based on the deviations of cant as well as the vertical and lateral position of the rail [15], see chapter 3 for more details. A high QS-ratio means smaller deviations from the rails' nominal position. It was found that a lower QS-ratio increased the scatter in loading and thus increased the standard deviation for both normal distributions. Regarding overloads registered, they increased with an increasing number of switches and crossings. The number of overloads also increased with a lower QS-ratio, however it was noted that this increase might be caused by other factors as well.

2.3 Correlation analysis

Since the assumption of this study is that track quality influences onboard measurement, it is reasonable to state that onboard measurements are dependent on track quality. A regression analysis is a common method to determine the relationship between two dependent variables [16]. For a linear regression, the coefficient of determination, R^2, gives an indication of how well the regression fits the data. An R^2 value of 1 indicates a perfect fit of the linear regression to the data. Another measurement of correlation is Pearson's coefficient of correlation [17]. It ranges from -1 to 1, where -1 indicates a perfect negative correlation, 0 indicates no correlation and 1 indicates a perfect positive correlation. Pearson's coefficient is only valid if the variables are paired and independent, and they should be normally distributed.

3

Track data

The western main line connects Stockholm and Gothenburg and is one of the main passenger lines in the Swedish railway network [18]. It is a fully electrified, double track railway. The SJ X40 runs revenue traffic on the western main line from Gothenburg to Hallsberg [19], and this part of the western main line makes the foundation for this study. The SmartSet® measurements are divided into six track sections: Gothenburg-Alingsås, Alingsås-Herrljunga, Herrljunga-Skövde, Skövde-Töreboda, Töreboda-Laxå and Laxå-Hallsberg. For each track section, the quality index QS is used as a measurement of track quality. QS is defined as

$$QS = 150 - \frac{100}{3}\left(\frac{SDH}{SDH_{gr}} + 2\frac{SDSAM}{SDSAM_{gr}}\right), \tag{3.1}$$

where SDH is the standard deviation of the rails vertical position and $SDSAM$ is the standard deviation of the sum of rail cant and the outer rails lateral position [15],[20]. SDH_{gr} and $SDSAM_{gr}$ are comfort limits for SDH and $SDSAM$ in the speed class of the track. A higher QS-ratio means less deviation from the nominal geometry of the track, thus indicating higher quality track. The maximum value of QS is 150, where a value above 100 can be considered as high quality track.

For each track section, the QS-ratio was manually retrieved from Trafikverket's system Optram [8] for each kilometer of track. Seven time periods were used, dating from late 2021 through 2022. These consist of all complete measurement runs in the given timespan. If a kilometer has been split into two or more measurements, an average of the measurements have been used instead. This is often the case where switches or stations are located. Both the average and the median for each section is presented, where a higher difference between the average and the median mainly indicates more sections with a low QS, usually stations or switches, in relation to the total length of the section. For clarity, track where trains run in a northern direction (Gothenburg-Hallsberg) will be referred to as northern track, and southern track for the opposite direction (Hallsberg-Gothenburg). An overview of each track section is shown in appendix A.

3.1 Gothenburg-Alingsås

The track section Gothenburg-Alingsås is characterised by multiple curves in both directions and switches along the way. More frequent load spikes can be expected from this track section. The average QS-ratio is shown in table 3.1 for the northern track and table 3.2 for the southern track. The track quality is high, with the southern track having a notably higher average than the northern track. A rather high disparity between average and median confirms the high number of switches. It is important to note, however, that the QS data included only stretches from Alingsås to Partille. The last part towards Gothenburg is not included.

Table 3.1: Average QS for Partille-Alingsås, northern track

Date	**Average**	**Median**
November 2022	100.587	103.5
September 2022	100.394	102
August 2022	101.769	104
July 2022	101.062	103
March 2022	102.230	103
January 2022	103.868	104.167
December 2021	No data	No data

Table 3.2: Average QS for Partille-Alingsås, southern track

Date	**Average**	**Median**
November 2022	115.103	118
September 2022	116.396	120.167
August 2022	116.725	120.5
July 2022	117.373	120.5
March 2022	117.010	121.167
January 2022	115.120	119
December 2021	No data	No data

3.2 Alingsås-Herrljunga

With a moderate amount of curves in both direction and a low number of switches, the section Alingsås-Herrljunga can be expected to have a medium frequency of load spikes. The QS ratio for the northern track is shown in table 3.3, and the southern track's QS ratio is shown in figure 3.4. A low disparity between average and median confirms a low number of switches, and the overall track quality is high with the southern track having a slightly higher average.

Table 3.3: Average QS for Alingsås-Herrljunga, northern track

Date	**Average**	**Median**
December 2022	107.946	109
September 2022	108.244	110
August 2022	109.103	110
June 2022	106.597	107.5
March 2022	109.119	111
January 2022	102.960	105.5
December 2021	109.856	112

Table 3.4: Average QS for Alingsås-Herrljunga, southern track

Date	**Average**	**Median**
December 2022	111.475	112.5
September 2022	111.028	112
August 2022	111.649	113
June 2022	112.910	113.5
March 2022	111.424	113
January 2022	108.751	109
December 2021	113.038	115

3.3 Herrljunga-Skövde

Herrljunga-Skövde is a longer section of track, with a moderately high number of curves in both directions as well as multiple switches. However, due to the length of the section, the relative frequency of load spikes is expected to be on the low end. The average QS is shown in table 3.5 and 3.6 for the northern and southern track respectively. The northern track have a slightly higher average QS, but the quality is high for both tracks.

Table 3.5: Average QS for Herrljunga-Skövde, northern track

Date	**Average**	**Median**
December 2022	115.009	119
September 2022	113.880	118
August 2022	113.925	117.5
June 2022	112.730	116.2
March 2022	114.780	118
January 2022	113.219	117
December 2021	116.677	120.5

Table 3.6: Average QS for Herrljunga-Skövde, southern track

Date	**Average**	**Median**
December 2022	109.577	113
September 2022	106.085	107
August 2022	106.365	107
June 2022	109.375	110
March 2022	107.555	108.5
January 2022	105.999	108.5
December 2021	110.440	112

3.4 Skövde-Töreboda

The track section Skövde-Töreboda is a rather short, very straight section with no notable curves. It also has a low number of switches along the way. Due to the unique layout of this section, a very low number of load spikes is expected with a low amount of external factors influencing the train ride along the track. Table 3.7 shows the average QS for the northern track and table 3.8 shows it for the southern track.

Table 3.7: Average QS for Skövde-Töreboda, northern track

Date	**Average**	**Median**
December 2022	115.740	119.5
September 2022	113.746	117.5
August 2022	113.903	117.5
June 2022	112.871	116
March 2022	112.200	116
January 2022	110.900	114.5
December 2021	113.708	118

Table 3.8: Average QS for Skövde-Töreboda, southern track

Date	**Average**	**Median**
December 2022	106.535	110
September 2022	105.048	109
August 2022	104.679	109
May 2022	109.471	111.5
March 2022	104.848	108
January 2022	103.724	106
December 2021	106.854	109.5

3.5 Töreboda-Laxå

Töreboda-Laxå is a section with a moderately low number of curves, however significant curves in both directions exists. It also has a low number of switches. Load spikes are expected, but not to a high frequency. The average QS for the northern and southern track respectively is shown in table 3.9 and 3.10. Both tracks have a high quality, with the northern having a slightly higher average QS.

Table 3.9: Average QS for Töreboda-Laxå, northern track

Date	**Average**	**Median**
December 2022	113.096	115
September 2022	110.933	113
August 2022	112.386	114
June 2022	111.427	112
March 2022	111.852	114.5
January 2022	108.906	110.5
December 2021	112.444	115.25

Table 3.10: Average QS for Töreboda-Laxå, southern track

Date	**Average**	**Median**
December 2022	111.838	112.85
September 2022	110.239	110.5
August 2022	108.807	109.8
May 2022	112.385	112.3
March 2022	106.923	108.3
January 2022	106.759	109
December 2021	110.113	112

3.6 Laxå-Hallsberg

This track section is on the shorter end, with a low number of curves. The amount of switches on the section is high, mainly related to the railway yard in Hallsberg, however that part of the track is not included in the QS data. Table 3.11 shows the average QS for the northern track and 3.12 shows it for the southern track. Both tracks have a similar high track quality, with the northern track having a slightly higher average QS.

Table 3.11: Average QS for Laxå-Hallsberg, northern track

Date	**Average**	**Median**
December 2022	112.492	116
September 2022	108.633	113
August 2022	109.867	114.5
June 2022	108.417	112
March 2022	110.917	115
January 2022	108.725	112
December 2021	112.458	115.5

Table 3.12: Average QS for Laxå-Hallsberg, southern track

Date	**Average**	**Median**
December 2022	110.242	113.5
September 2022	105.725	109
August 2022	105.850	108.5
May 2022	109.508	112
March 2022	107.267	111
January 2022	109.700	113
December 2021	109.483	112.5

3.7 Limitations and potential sources of errors

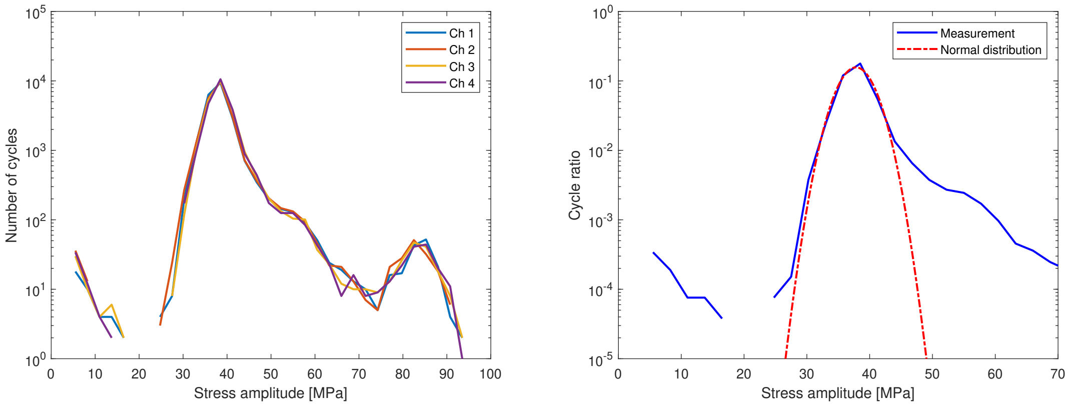
A limitation in track data is that only seven full measurements of the track sections exists. It is limited by the amount of times Trafikverket carried out measurements with a specialized measurement vehicle, leading to possible challenges when making comparisons. Moreover, all track sections in this study are considered to feature high quality track. The western main line is a highly maintained track. Thus, no measurements will be available from lower quality track. This might limit how visible effects of track quality are on onboard measurement systems.

4

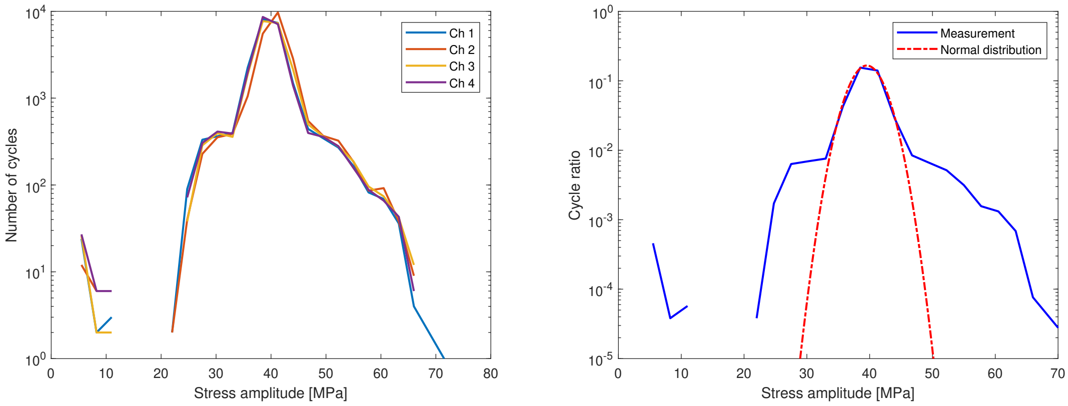
Onboard measurements

The onboard measurements were recorded by the system SmartSet® developed by Lucchini RS, along the sections of track presented in chapter 3. As stated in chapter 2, the system is mounted on the outer axle of an SJ X40 passenger train [4]. This implies that the instrumented axle is always running as either the very first or the very last axle of the train, depending on the train's travelling direction. However, the train can also be coupled to another unit, which can place the instrumented wheelset adjacent to the second unit. For each channel, the strain measurements are converted to stress measures and stored in a matrix through a rainflow counting algorithm, where the rows in the matrix represents mean stress for a cycle and the columns represent stress amplitude. Each row and column represents stress increments of 2.75 MPa. Thus, a registered cycle adds to the cumulative total of the cell representing the pertinent mean stress and stress amplitude. The system is designed to upload the data at designated stations, and the matrix is reset once the data have been uploaded. Thus, a file will have the start and end point, as well as the total number of cycles from which the distance travelled can be calculated using the circumference of the wheels.

This study have used a similar method as is described by Maglio *et al.* [5]. Each matrix for the track sections of interest was converted to a stress spectrum. Then, a truncated normal distribution was fitted to the data representing quasi-static loading using a function created by Ryabov [21] to investigate if a difference in track quality can be seen. Quasi-static loading is chosen to limit the influence of external factors that introduces time-dependent loading. The truncation points have been manually adjusted based on the gradient of the data and the increments of 2.75 MPa to ensure a representative fit of the normal distribution. An example of two stress spectra is shown in figure 4.1, where leading denotes when the wheelset is in the leading position, and trailing denotes when it is in the trailing position. Looking at data when the axle is in a leading position, the first part of the stress spectra with the highest number of cycles represent the quasi-static loading of the axle. The higher stress amplitudes originates from overload sources, such as switches or narrow curves. For the current purpose of estimating track quality, only the quasi-static loading has been used to better represent regular operation of the track. When the train is operating in the opposite direction and the wheelset is trailing, the shape of the stress spectra changes noticeably. An increase in low amplitude cycles occurs together with a decrease in overloads, compared to the leading position. Thus, the normal distribution has to be truncated from the left as well. The mean, standard deviation, and truncation interval have been stored for each analysed stress spectra, however only the standard deviation have been used in the analysis and will be the only value presented. The four channels, corresponding to the four measurement points of the axle as discussed in section 2.1, are denoted Ch. 1, 2, 3 and 4. In some cases, the measurement data for one of the four channels were faulty and could not be used. The channel in question had a different number of cycles registered compared to the other channels, with the resulting stress spectrum being discontinuous and clearly faulty. These measurements have been removed and are shown in the tables as an empty cell.



(a) Stress spectra - Leading **(b)** Normal distribution - Leading

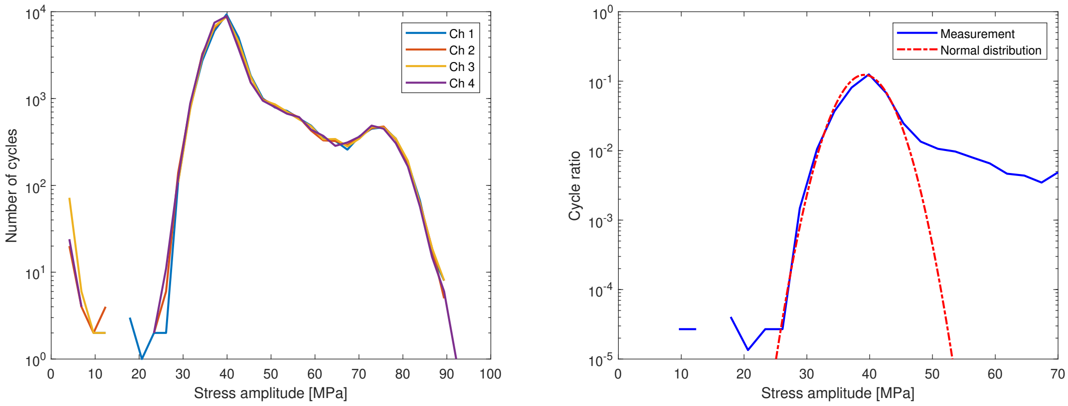


(c) Stress spectra - Trailing **(d)** Normal distribution - Trailing

Figure 4.1: An example of stress spectra and their normal distributions

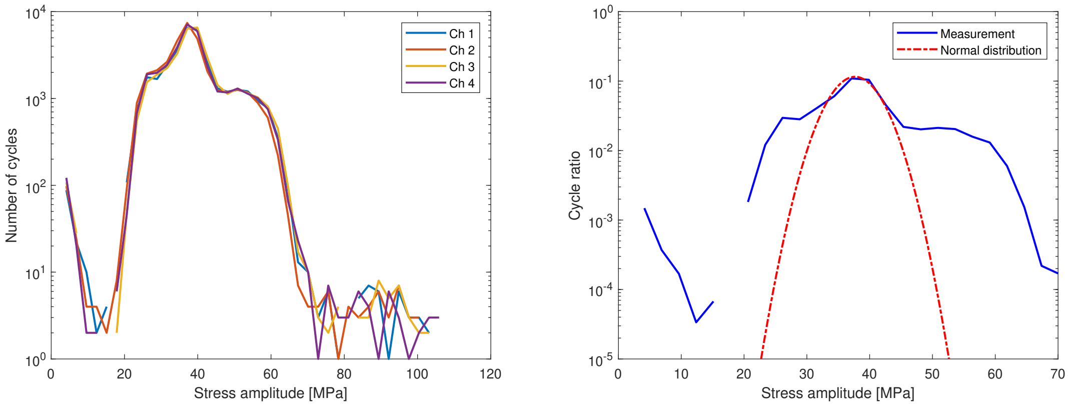
4.1 Gothenburg-Alingsås

The stress spectra from the section Gothenburg-Alingsås shows a significant spread in measured stresses with a significant amount of overloads. In the leading position, the wheelset experiences multiple cycles of stresses over 70 MPa. When trailing, the amount of significant overloads decreases, with an increase in cycles both slightly lower and slightly higher than the mean stress of quasi-static loading, in the range of 30-45 MPa. This behaviour can be linked to the amount of switches from the section, as well as the amount of curves. The fitted normal distributions have a large standard deviation, both when the wheelset is leading and when it is trailing. Figure 4.2 shows examples of stress spectra and normal distributions, and table 4.1 and 4.2 show the standard deviation for each run analysed. For this track section there is a discrepancy between onboard measurement and track data. In contrast to the track data which only covers Alingsås to Partille, the onboard measurements covers Alingsås to Gothenburg.



(a) Stress spectra - Leading

(b) Normal distribution - Leading



(c) Stress spectra - Trailing

(d) Normal distribution - Trailing

Figure 4.2: Examples of stress spectra and fitted normal distributions for Gothenburg-Alingsås

Table 4.1: Gothenburg-Alingsås, Leading position. Standard deviation for each channel and the truncation interval [MPa]

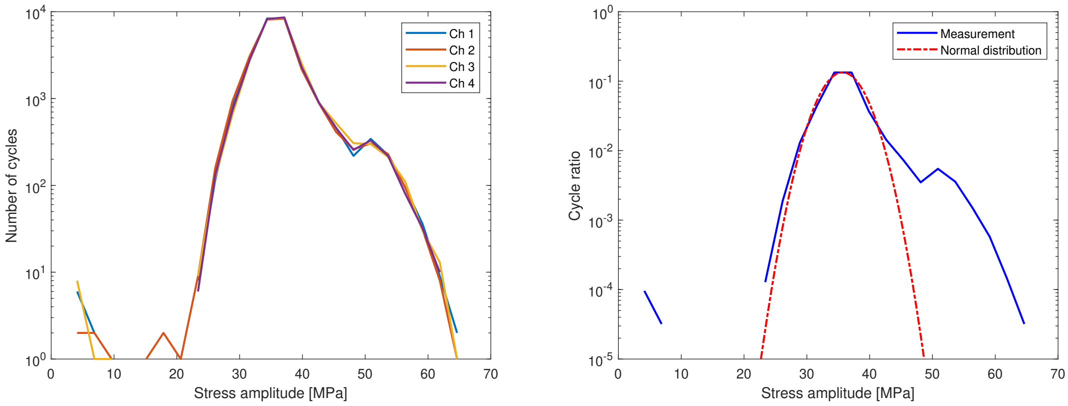
Date	**Direction**	**Ch.1**	**Ch.2**	**Ch.3**	**Ch.4**	**Interval**
2022-02-04	North	4.957	3.877	4.767	3.842	20-42
2022-08-20	South	3.235	3.218	3.156	3.079	25-46
2022-08-22	South	3.279	3.221	3.141	3.114	20-46
2022-10-01	South	2.682	2.814	2.638	2.607	25-46
2022-11-01	South	-	3.312	3.170	3.108	25-46
2022-12-01	South	3.425	3.690	3.058	3.533	25-46
2022-12-04	South	3.702	3.950	3.562	4.113	25-46
2022-12-05	South	3.450	3.630	3.313	3.659	25-46

Table 4.2: Gothenburg-Alingsås, Trailing position. Standard deviation for each channel and the truncation interval [MPa]

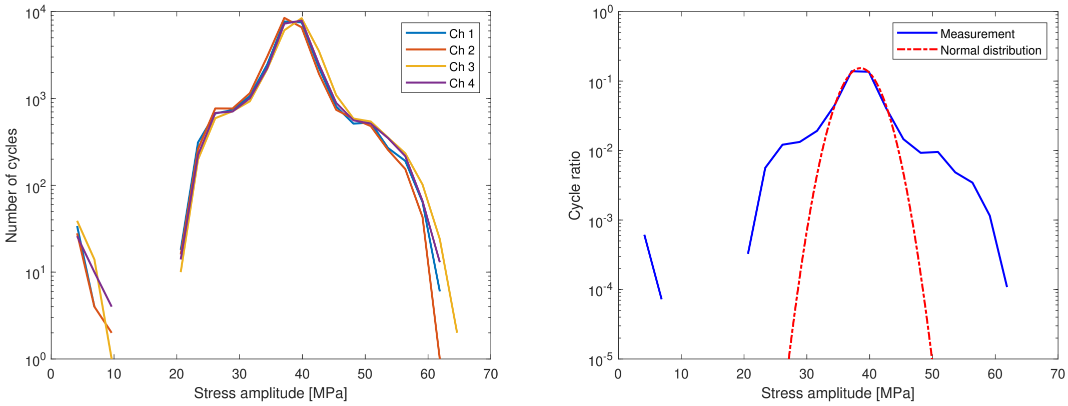
Date	**Direction**	**Ch.1**	**Ch.2**	**Ch.3**	**Ch.4**	**Interval**
2022-02-04	South	3.689	3.537	3.750	3.732	32-42
2022-04-18	South	3.401	3.303	3.414	3.171	32-42
2022-08-20	North	3.458	3.707	3.359	3.389	35-46
2022-08-26	North	3.934	3.911	3.779	3.705	32-46
2022-10-01	North	3.522	3.478	3.478	3.525	32-46
2022-11-01	North	-	3.600	3.626	3.606	32-46
2022-12-01	North	3.434	3.722	3.904	3.453	32-46
2022-12-04	North	3.551	3.470	3.471	3.453	32-46

4.2 Alingsås-Herrljunga

With a lower amount of overloads, the section Alingsås-Herrljunga shows measurements with a smaller spread. For both leading and trailing positions of the wheelset, there are hardly any cycles over 70 MPa. The trailing position shows the characteristic behaviour of an increase in cycles both slightly lower and slightly higher than the mean of quasi-static loading, around 30-45 MPa. The standard deviation for the fitted normal distributions are moderately large, both for leading and trailing positions of the wheelset. Examples of stress spectra and their normal distributions are shown in figure 4.3, and the standard deviation for each run are shown in table 4.3 for leading position and table 4.4 for trailing position.



(a) Stress spectra - Leading **(b)** Normal distribution - Leading



(c) Stress spectra - Trailing **(d)** Normal distribution - Trailing

Figure 4.3: Examples of stress spectra and fitted normal distributions for Alingsås-Herrljunga

Table 4.3: Alingsås-Herrljunga, Leading position. Standard deviation for each channel and the truncation interval [MPa]

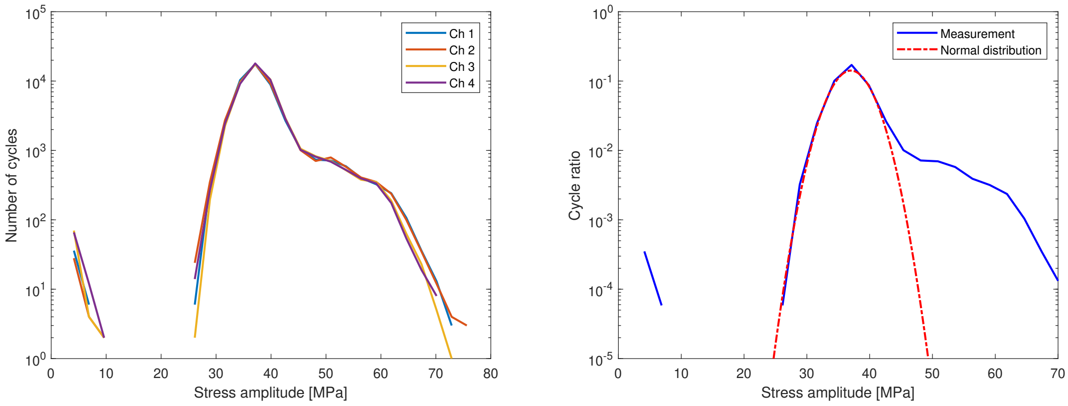
Date	**Direction**	**Ch.1**	**Ch.2**	**Ch.3**	**Ch.4**	**Interval**
2022-02-04	North	2.592	2.664	2.852	2.715	20-42
2022-08-20	South	2.908	-	2.671	2.701	20-45
2022-08-22	South	2.980	3.073	2.992	2.974	25-42
2022-10-01	South	2.975	3.045	2.887	2.880	25-45
2022-10-15	South	3.115	3.242	3.111	3.052	25-45
2022-11-01	South	-	2.881	2.698	2.658	32-45
2022-11-06	South	2.766	2.843	2.808	2.731	25-42
2022-12-01	South	3.006	3.299	3.284	3.491	25-47
2022-12-04	South	2.918	3.020	3.124	3.173	35-47
2022-12-05	South	3.016	2.733	2.976	2.941	35-45

Table 4.4: Alingsås-Herrljunga, Trailing position. Standard deviation for each channel and the truncation interval [MPa]

Date	**Direction**	**Ch.1**	**Ch.2**	**Ch.3**	**Ch.4**	**Interval**
2022-02-04	South	3.060	2.999	3.009	3.017	20-42
2022-04-18	South	3.061	2.851	2.896	2.881	32-42
2022-08-20	North	2.597	2.602	2.905	2.612	34-45
2022-08-26	North	2.821	2.672	2.903	2.742	32-45
2022-08-27	North	2.815	2.733	3.041	2.849	32-45
2022-08-30	North	2.880	2.934	3.033	2.884	32-45
2022-09-18	North	2.909	2.831	2.947	2.888	32-45
2022-11-01	North	2.856	2.738	3.035	2.821	35-45
2022-11-06	North	3.031	2.930	3.827	3.154	32-42
2022-12-01	North	2.644	2.681	2.841	2.611	35-45
2022-12-04	North	2.653	2.556	2.897	2.541	35-45

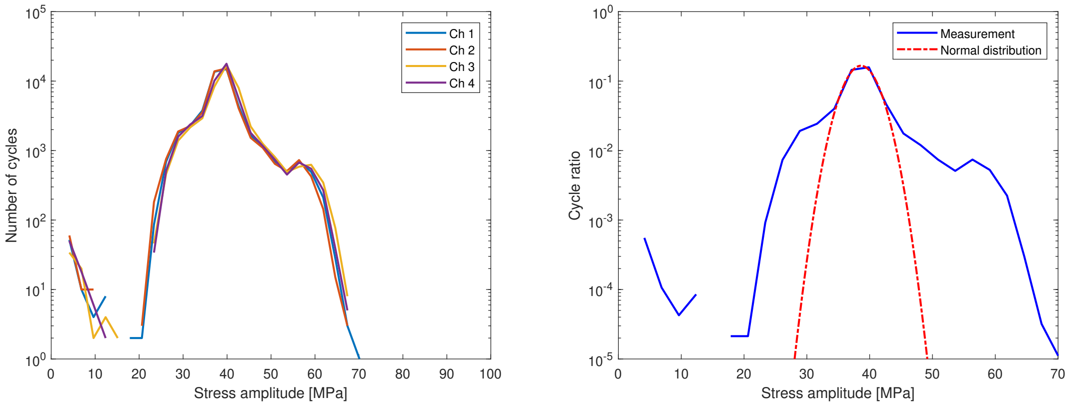
4.3 Herrljunga-Skövde

The section Herrljunga-Skövde shows similar measurements to the section Alingsås-Herrljunga, but with less scatter in the measured stress cycles. Since it is one of the longer sections, more cycles are registered which, to some extent, leads to smoother stress spectra, visible in figure 4.4. The standard deviations, shown in table 4.5 and 4.6 for leading and trailing positions of the wheelset respectively, are towards the lower end.



(a) Stress spectra - Leading

(b) Normal distribution - Leading



(c) Stress spectra - Trailing

(d) Normal distribution - Trailing

Figure 4.4: Examples of stress spectra and fitted normal distributions for Herrljunga-Skövde

Table 4.5: Herrljunga-Skövde, Leading position. Standard deviation for each channel and the truncation interval [MPa]

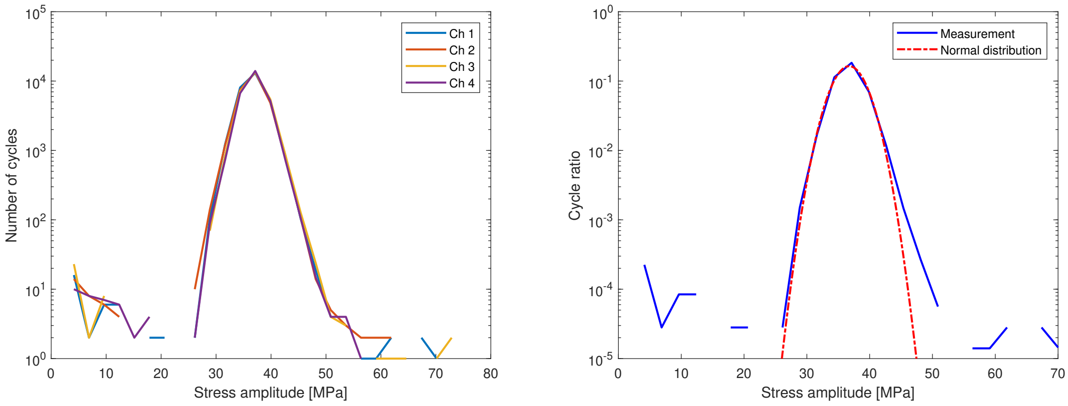
Date	**Direction**	**Ch.1**	**Ch.2**	**Ch.3**	**Ch.4**	**Interval**
2022-02-04	North	2.562	2.494	2.672	2.556	20-43
2022-08-20	South	2.989	-	2.989	2.930	25-49
2022-10-01	South	2.816	2.872	2.779	2.804	25-46
2022-10-15	South	2.734	2.791	2.697	2.635	25-46
2022-12-01	South	3.085	3.156	3.132	3.245	25-49
2022-12-04	South	3.201	3.232	3.259	3.289	25-49

Table 4.6: Herrljunga-Skövde, Trailing position. Standard deviation for each channel and the truncation interval [MPa]

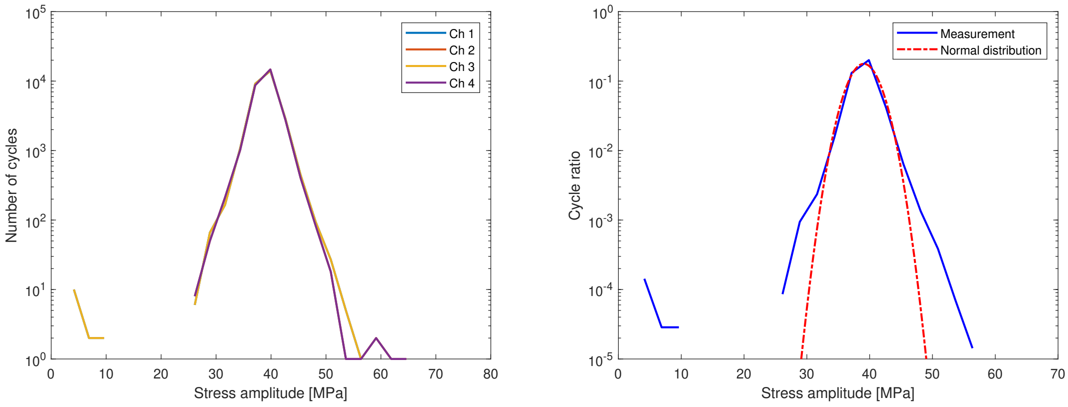
Date	**Direction**	**Ch.1**	**Ch.2**	**Ch.3**	**Ch.4**	**Interval**
2022-02-04	South	3.271	3.222	3.218	3.216	25-43
2022-08-26	North	2.476	2.385	2.829	2.531	32-43
2022-09-18	North	2.512	2.445	2.681	2.578	32-43
2022-11-01	North	2.396	2.330	2.562	2.394	34-46
2022-12-01	North	2.368	2.393	2.484	2.289	34-46
2022-12-04	North	2.432	2.451	2.658	2.449	36-49

4.4 Skövde-Töreboda

Skövde-Töreboda, as described in section 3.4, is a unique section of track. The data shows hardly any overloads, and the characteristic behaviour, an increase in stress levels lower than the quasi-static mean, when the wheelset is trailing is toned down. This is confirmed by the stress intervals including these cycles and still retaining a low standard deviation for the fitted normal distribution. Thus, the stress spectra for the leading and the trailing position of the wheelset are very similar, see figure 4.5. Tables 4.7 and 4.8 contain the standard deviations for the leading and trailing positions of the wheelset, which shows the lowest spread in the data for all track sections analysed. However, one run showed characteristics of both leading and trailing positions and it could not be verified from which position the measurements originated. This run was included in the data for leading position.



(a) Stress spectra - Leading **(b)** Normal distribution - Leading



(c) Stress spectra - Trailing **(d)** Normal distribution - Trailing

Figure 4.5: Examples of stress spectra and fitted normal distributions for Skövde-Töreboda

Table 4.7: Skövde-Töreboda, Leading position. Standard deviation for each channel and the truncation interval [MPa]

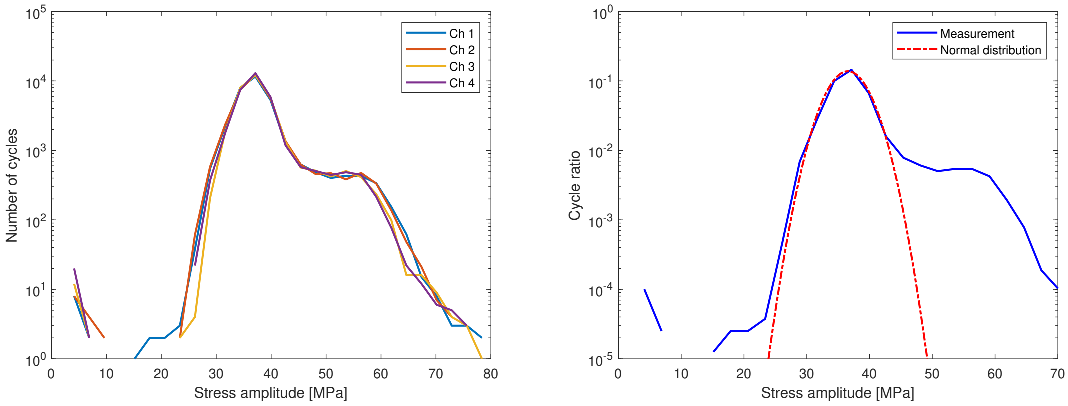
Date	**Direction**	**Ch.1**	**Ch.2**	**Ch.3**	**Ch.4**	**Interval**
2022-02-04	North	1.952	1.953	2.002	1.838	20-42
2022-06-23*	South	2.698	2.650	2.779	2.693	20-47
2022-08-20	South	2.622	1.702	2.681	2.665	25-47
2022-10-01	South	2.432	2.409	2.344	2.268	25-45
2022-10-15	South	2.378	2.392	2.427	2.383	25-47
2022-12-01	South	2.429	2.360	2.476	2.465	25-47
2022-12-04	South	2.343	2.305	2.462	2.455	25-47
2022-12-17	South	2.608	2.707	2.663	2.963	20-47
2022-12-19	South	2.318	2.462	2.608	2.989	25-47

Table 4.8: Skövde-Töreboda, Trailing position. Standard deviation for each channel and the truncation interval [MPa]

Date	**Direction**	**Ch.1**	**Ch.2**	**Ch.3**	**Ch.4**	**Interval**
2022-02-04	South	2.484	2.505	2.507	2.452	20-45
2022-08-26	North	2.136	2.127	2.229	2.153	20-45
2022-08-28	North	2.222	2.223	2.386	2.254	20-45
2022-09-18	North	2.191	2.202	2.289	2.241	20-45
2022-11-01	North	2.250	2.209	2.250	2.209	20-47
2022-12-01	North	2.240	2.237	2.358	2.157	20-47
2022-12-04	North	2.242	2.182	2.381	2.182	20-47

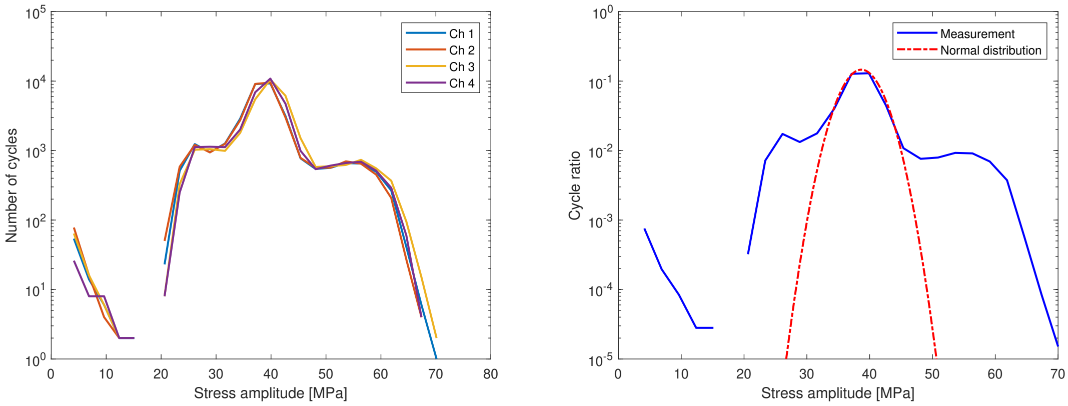
4.5 Töreboda-Laxå

Töreboda-Laxå shows stress spectra similar to those of the sections Alingsås-Herrljunga and Herrljunga-Skövde. The spread in measured stresses are moderate, with overloads existing for the leading position of the wheelset and the characteristic behaviour for the trailing position clearly visible. The standard deviations from the fitted normal distributions are moderately large. Figure 4.6 shows the stress spectra and their fitted normal distributions, and tables 4.9 and 4.10 shows the standard deviations for leading and trailing positions of the wheelset, respectively.



(a) Stress spectra - Leading

(b) Normal distribution - Leading



(c) Stress spectra - Trailing

(d) Normal distribution - Trailing

Figure 4.6: Examples of stress spectra and fitted normal distributions for Töreboda-Laxå

Table 4.9: Töreboda-Laxå, Leading position. Standard deviation for each channel and the truncation interval [MPa]

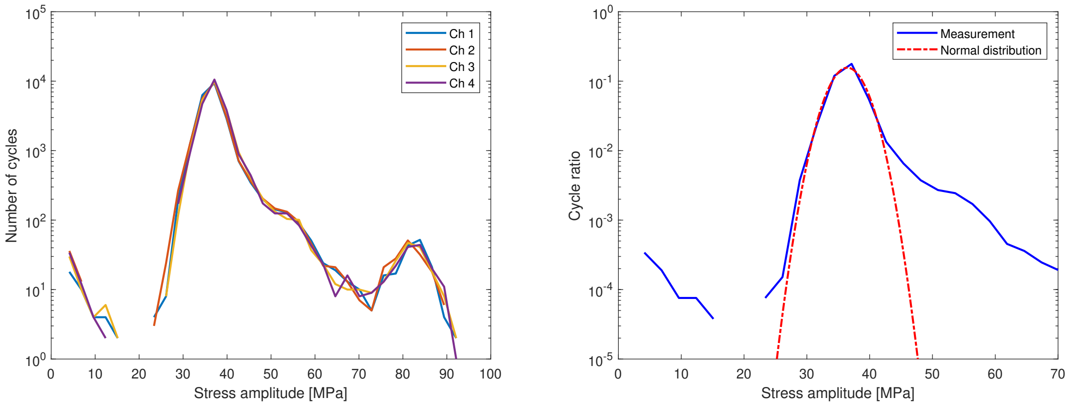
Date	Direction	Ch.1	Ch.2	Ch.3	Ch.4	Interval
2022-02-04	North	2.846	2.880	3.064	2.985	25-43
2022-08-20	South	3.041	3.122	2.906	2.836	25-49
2022-10-01	South	2.897	2.938	2.708	2.713	25-46
2022-10-15	South	2.707	2.764	2.607	2.483	25-46
2022-12-01	South	2.989	3.118	3.081	3.305	25-49
2022-12-04	South	3.035	3.077	3.124	3.210	25-49
2022-12-17	South	2.746	3.190	3.166	3.049	25-49
2022-12-19	South	2.538	3.054	3.310	3.165	25-49

Table 4.10: Töreboda-Laxå, Trailing position. Standard deviation for each channel and the truncation interval [MPa]

Date	Direction	Ch.1	Ch.2	Ch.3	Ch.4	Interval
2022-02-04	South	2.727	2.646	2.704	2.728	28-43
2022-08-26	North	2.727	2.662	2.809	2.689	32-46
2022-08-28	North	2.757	2.727	2.873	2.755	34-49
2022-09-18	North	2.842	2.796	2.864	2.776	32-46
2022-11-01	North	2.732	2.689	2.802	2.680	34-49
2022-12-01	North	2.876	2.890	3.082	2.835	32-49

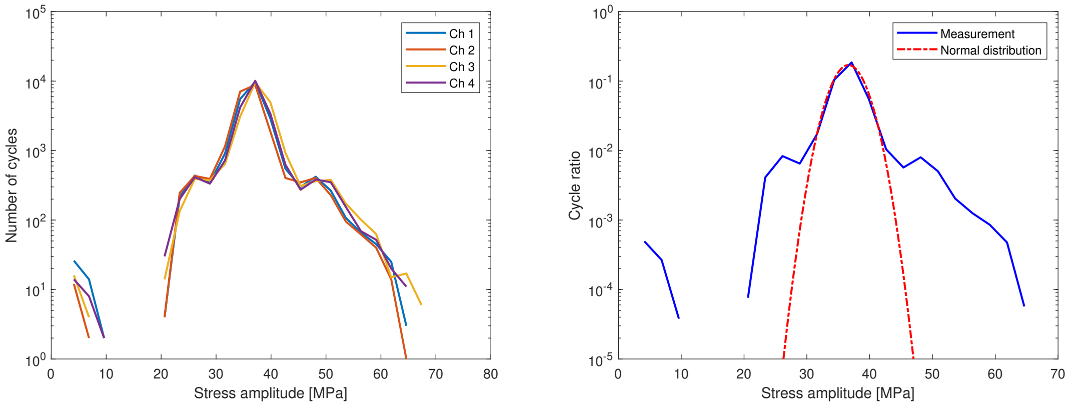
4.6 Laxå-Hallsberg

The section Laxå-Hallsberg shows a similar behaviour to the section Gothenburg-Alingsås, with a significant amount of overloads over 70 MPa for the leading position of the wheelset. In the trailing position, the wheelset experiences numerous cycles both higher and lower than the quasi-static mean stress, around 30-45 MPa. This can, once again, be linked to the number of switches along the section of track. On the other hand, the standard deviations for the fitted normal distributions are on the lower end. Due to the track being mostly straight with a low number of significant curves, it is reasonable that the spread of the normal distribution is lower. The stress spectra and their normal distributions are shown in figure 4.7 and the standard deviations are shown in table 4.11 for the leading position of the wheelset and table 4.12 for the trailing position. Similar to the track section Skövde-Töreboda, for one of the runs of the train it could not be verified if the wheelset was in the leading or trailing position. The data showed characteristics of both leading and trailing, and the run was placed as a leading position run.



(a) Stress spectra - Leading

(b) Normal distribution - Leading



(c) Stress spectra - Trailing

(d) Normal distribution - Trailing

Figure 4.7: Examples of stress spectra and fitted normal distributions for Laxå-Hallsberg

Table 4.11: Laxå-Hallsberg, Leading position. Standard deviation for each channel and the truncation interval [MPa]

Date	Direction	Ch.1	Ch.2	Ch.3	Ch.4	Interval
2022-02-04	North	2.542	2.502	2.717	2.501	25-43
2022-06-23*	South	3.239	3.099	3.225	3.087	25-46
2022-08-20	South	2.829	2.825	2.813	2.704	25-49
2022-10-01	South	2.553	2.607	2.562	2.509	25-46
2022-12-01	South	2.373	2.505	2.516	2.548	25-46
2022-12-04	South	2.702	2.809	2.939	2.923	25-49
2022-12-17	South	2.926	3.003	3.082	2.976	25-49
2022-12-19	South	2.666	2.715	2.901	2.991	25-49

Table 4.12: Laxå-Hallsberg, Trailing position. Standard deviation for each channel and the truncation interval [MPa]

Date	Direction	Ch.1	Ch.2	Ch.3	Ch.4	Interval
2022-02-04	South	2.478	2.353	2.440	2.416	28-43
2022-08-26	North	2.346	2.312	2.385	2.300	32-46
2022-08-28	North	2.553	2.520	2.689	2.577	32-49
2022-09-18	North	2.472	2.412	2.447	2.453	32-46
2022-12-01	North	2.407	2.447	2.486	2.337	32-46

4.7 Limitations and potential sources of errors

It is noticeable that the amount of runs used are very limited. This is due to a known issue with the computer on the SmartSet®, where the data matrix is not always uploaded to the server at a designated station. Thus, the matrix is not reset, instead it keeps adding cycles to the matrix. One run from Gothenburg to Hallsberg corresponds to approximately 290 km of data. The rest of the route, Hallsberg to Stockholm corresponds to approximately 260 km of data. Thus, one run from Gothenburg to Stockholm should represent approximately 550 km of data. An example of where the computer has failed to upload data occurred between February 17th and April 18th of 2022, where a matrix containing 44 000 km of data was uploaded. Assuming that the train operated the route Stockholm-Gothenburg-Stockholm 75% of the time during this period, data corresponding to approximately 60 runs were not usable for the current study. It is important to note that the measurements are still valid for measuring strains on the axle, however for the purpose of connecting the measurements to track quality, the matrix has to contain only data between two adjacent stations. The section of track where most runs were recorded from the year 2022 was Alingsås-Herrljunga with a total of 21 runs. Eleven were from the train going south and ten from the train going north. Continuing with the previous assumption that two months of data represent approximately 60 runs between Gothenburg and Stockholm, one year should contain approximately 360 runs. This means that only around 6% of the total data is useful for the current purpose. Note that this number is based on assumptions, so it should only be used as an indication of the amount of data that are not useful for the current purpose.

Moving on to potential sources of errors, there are a few that needs to be taken into consideration. Beginning with the different channels, it is intriguing that the measurements of the channels differ considerably in some of the runs. There is seemingly no pattern, such as one channel always giving higher measurements. Theoretically, given a perfect wheel, the measured stresses should be very similar resulting in almost equal stress spectra. This is not the case, and the reason has not been determined. Furthermore, the matrix stores the measurements in increments of 2.75 MPa. Thus, two cycles that differ by 0.1 MPa could be registered as having a difference of 2.75 MPa if one of the cycles is just over the threshold and the other is just below. It has not been studied if this specifically affect the resulting stress spectra. The truncation intervals are a potential source of error as well. Firstly, they have been manually determined which gives room for judgement errors. Moreover, the function used to calculate the normal distribution bases the resulting distribution partly on the stated interval. Given the stress increments of 2.75 MPa, the resulting normal distribution differs even if the stated interval is in the range of the same stress increments. An example would be that the stress increments are 40, 42.75 and 45.5 MPa. If the truncation interval is defined as 43, 44 or 45, the same stress cycles would be included for all three cases and should give the same normal distribution. However, these inputs would result in three different distributions. This was examined for multiple stress spectra, and the difference in standard deviation could range between 0.05-0.2 MPa.

Lastly, the condition of the train has not been taken into consideration at any point. It was not possible to verify when the wheelset had been reprofiled. A worn out wheelset could influence the measured stresses and the resulting stress spectra, compared to when it is newly reprofiled. This is an uncertainty in the data that needs to be taken into account when drawing conclusions. Moreover, the load on the wheelset from the train might vary between runs due to differences in the number of passengers. It should be noted, however, that since the instrumented axle is located at the very end of a motor unit below the driver's cabin, the influence of passenger loading should be limited.

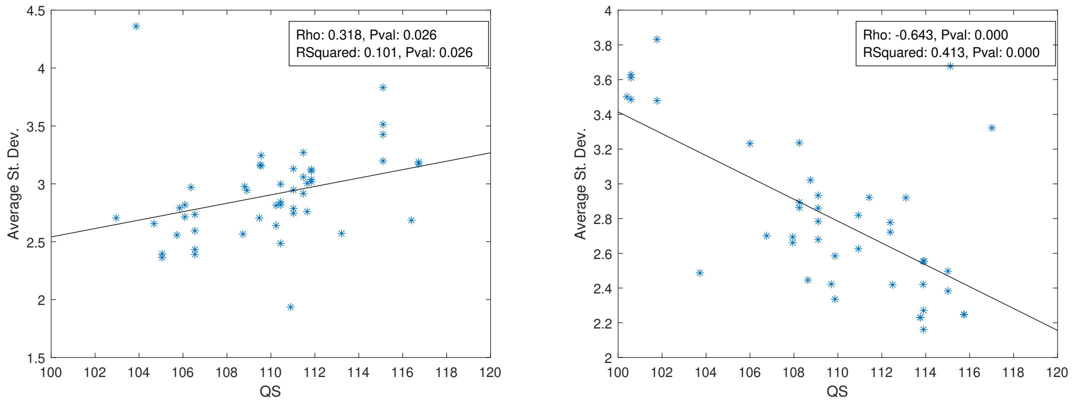
5

Comparison and correlations

To make a correlation analysis between the quality of track, measured by QS-ratio, and onboard measurements, in the form of a fitted normal distribution to the stress cycles, the data have been matched based on time. The most recent measurement of QS has been used for each run recorded in the onboard measurement data. The expected result would be that higher track quality should give a lower spread in the data, thus a lower standard deviation. However, the measurements are also affected by track geometry, especially the occurrence of switches and significant curves. The analysis has been performed in three steps: combined, track section specific and selective analysis, where a possible correlation is explored through regression analysis and Pearson's correlation coefficient.

5.1 Combined analysis

Looking at the data, it is clear that track layout dominates the outcome of the stress spectra. An example of this is the straight track section of Skövde-Töreboda which has standard deviations ranging between 1.95 and 2.70 MPa for channel 1. This differs significantly from the section Gothenburg-Alingsås, where the standard deviations for channel 1 ranges between 2.69 all the way to 4.96 MPa. Figure 5.1 shows a scatter plot of the standard deviations and their corresponding QS-ratios based on the date of the run. The combined measurements for the leading position of the wheelset show a weak linear regression, with a positive correlation coefficient. This is opposite to what would be expected for the relationship between track quality and onboard measurements. For the trailing position of the wheelset, there is a stronger regression with a negative correlation coefficient, however the regression is still rather weak. Both of these cases can be explained by the fact that the different track sections differ significantly in amount of switches and curves, both of which strongly influence the measurements. The implications are further discussed in chapter 6.



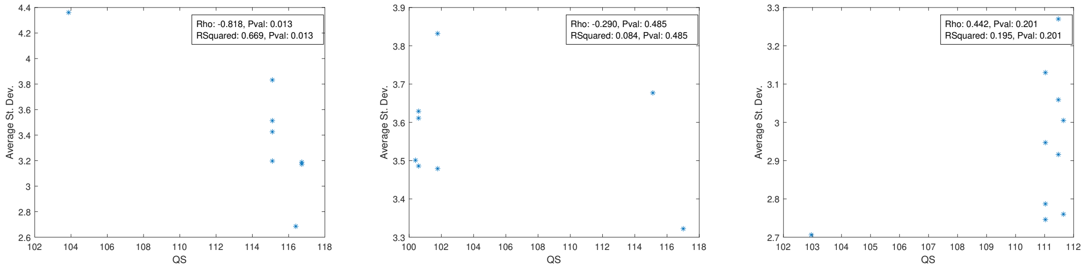
(a) Wheelset in leading position

(b) Wheelset in trailing position

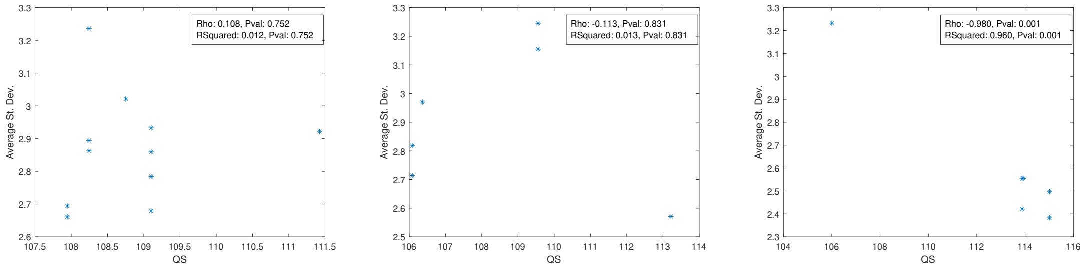
Figure 5.1: Scatter plot of standard deviations and their corresponding QS-ratios for all tracks combined

5.2 Track section specific analysis

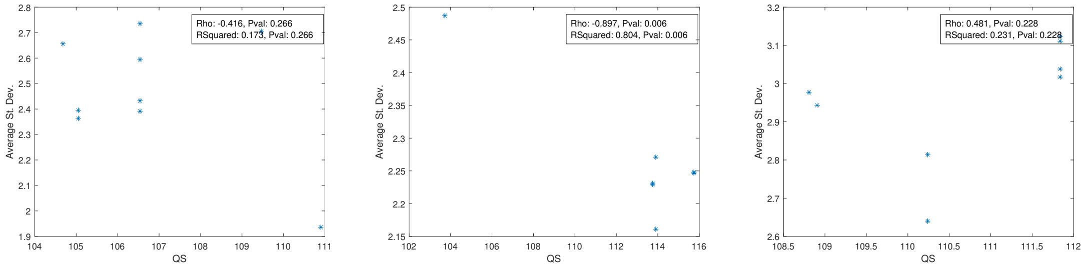
To remove the influence of differences in nominal track characteristics, the same analysis has been performed for each track section separately. However, this brings the issue of very low sample sizes. The results from this section should therefore only be used as an indication of a possible correlation, not as definitive results. Figure 5.2 shows the scatter plots for all track sections. Three sections show a strong regression with a negative correlation coefficient: Gothenburg-Alingsås with the wheelset in the leading position, Herrljunga-Skövde in the trailing position and Skövde-Töreboda in the trailing position. The sample sizes are 9, 6, and 7, respectively, which are all relatively small. All other track sections show weak regressions.



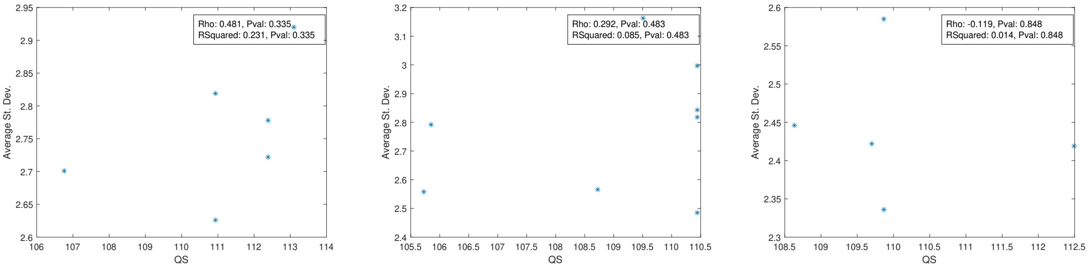
(a) Got-Al, leading **(b)** Got-Al, trailing **(c)** Al-Herr, leading



(d) Al-Herr, trailing **(e)** Herr-Skv, leading **(f)** Herr-Skv, trailing



(g) Skv-Tö, leading **(h)** Skv-Tö, trailing **(i)** Tö-Lax, leading



(j) Tö-Lax, trailing **(k)** Lax-Hall, leading **(l)** Lax-Hall, trailing

Figure 5.2: Scatter plot for each track section, denoted as: Got for Gothenburg, Al for Alingsås, Herr for Herrljunga, Skv for Skövde, Tö for Töreboda, Lax for Laxå, and Hall for Hallsberg

5.3 Selective analysis of Skövde-Töreboda

The track section of Skövde-Töreboda have been used as a test case since it has small effects of curves and switches. For this case, the leading and trailing measurements have been combined, with the motivation that the truncation interval has been determined in the same way for both leading and trailing. Thus, both models should be based on the same data. For the other track sections, using the leading truncation interval for trailing measurements would substantially increase the standard deviation. This was not the case for Skövde-Töreboda. The validity of this comparison could still be questioned, however it allows for a larger sample size which is useful because of the lack of valid data. Figure 5.3 shows the scatter plot, which indicates a weak regression but a possible correlation through a negative correlation coefficient. This might indicate a possible correlation between track quality and onboard measurement data because of the lack of switches and curves along the section, however the scatter is still quite significant.

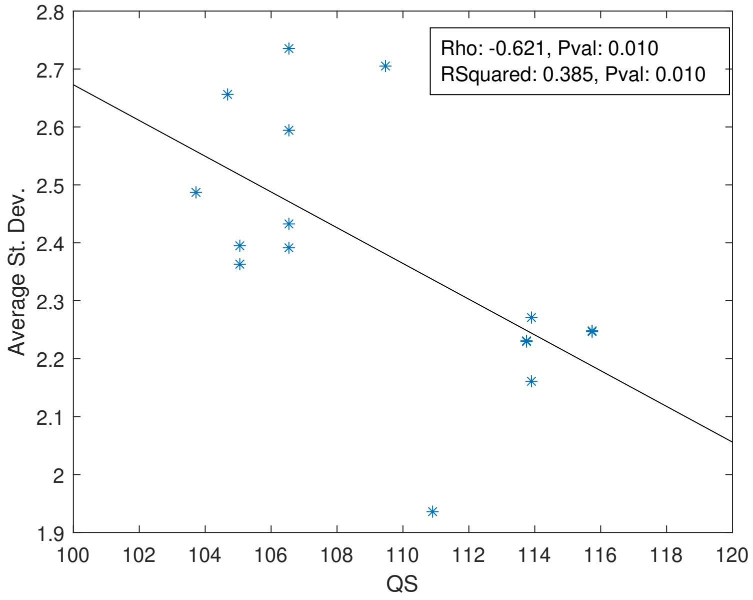


Figure 5.3: Scatter plot for Skövde-Töreboda, Leading and trailing combined

5.4 Limitations and sources of errors

There is a significant limitation regarding the connection between track measurements and onboard measurements. The comparison is limited by the amount of measurements that Trafikverket carried out, which in this case was seven times ranging from December 2021 through December 2022, thus limiting the available track data. Furthermore, all of these measurements have not been used because of a lack of runs with valid onboard measurement data. Thus, the QS-ratio used in the analysis might not accurately represent the status of the track because of the time difference between the track measurement and the onboard measurement run. Another limitation is the low population of valid runs with onboard measurements which makes the foundation for all comparisons. As discussed in section 4.7, the lack of valid data creates an issue in making a valid correlation analysis. The largest population in the track specific analysis is 11, with most of the sections having a lower sample size. This is in the region of being too small to make a regression analysis.

6

Discussion

This study has faced a number of challenges which have affected the choice of methods and the outcome. The discussion is split into three parts: Methods, Results, and Limitations. Each part is analysed through alternative methods or sources of uncertainty and errors to further examine the outcomes of the study.

6.1 Methods

The analysis of this study is rather narrow with a specific focus on the measurements. It is based on the work of Maglio *et al.* [6], and aims to further describe the effects track quality has on onboard measurements. However, this study only focuses on the part of the stress spectra that represents quasi-static loading, whereas Maglio *et al.* explored the effects on the stress spectra as a whole. The reason for this focus is to limit the effects of other factors than track quality, such as switches and curves, however this might eliminate some effects of track quality as well. One of the results Maglio *et al.* presented was that track quality also affected overloads in the stress spectra, and these effects will not be visible in this study. It will be important to keep this in mind when interpreting the results.

Looking at track quality, the general measurement of QS is used in this study. Trafikverket's guidelines state that this should only be used as an indication of track quality and that no actions should be taken only based on the QS-ratio of a track section [15],[20]. Thus, it could be questioned how accurate a correlation between only the QS-ratio and onboard measurements is. On the other hand, it can give an initial indication of a correlation, and further analysis can be carried out with more specific measurements of track quality. Since QS is based on both vertical and lateral deviations, further analysis separating the two could show separate effects of vertical and lateral deviation. As is the case for this study, a correlation was not found, and a basis for further analysis could not be formed, see section 6.2 for more information.

Moving on to the method of extracting stress spectra and fitting the normal distribution, the choice of manually truncating the data should be questioned. It opens the door to effects of judgement affecting the results. An option would be to create an algorithm that truncates the data based on the gradient. However, a perfect fit could not always be achieved, and since the normal distribution changes even when adjusting the interval between stress increments, an algorithm might not always be accurate. With a limited amount of data, a manual truncation is reasonable, but if this method were to be implemented on a larger scale, it would be necessary to develop a truncation algorithm.

Lastly, the validity of the correlation analysis can be questioned. The use of a linear regression and Pearson's correlation coefficient assumes a linear relation between track quality and onboard measurements. Furthermore, Pearson's correlation coefficient requires that the data are independent and are normally distributed. One might argue that the track quality measurements are not independent, since the same QS-ratio is used for multiple runs of the onboard measurements. However, there are no other option than to use the most recent track quality measurements for each run. It can also be questioned if the track quality measurements and the model of using the standard deviation for the onboard measurements are true normal distributions. Once again, it needs to be kept in mind when interpreting the results.

6.2 Results

Starting with the onboard measurements, it is clear that the characteristics of the track have a substantial influence on the resulting stress spectra. The best examples of this are Gothenburg-Alingsås and Laxå-Hallsberg, which both have a huge increase in overload cycles that can be linked to the amount of switches that exists along these track sections. The counterpart, Skövde-Töreboda, shows a very low number of cycles outside the fitted normal distribution, making it a good representation of the quasi-static load on the axle. Furthermore, it is visible that an increase in curves have an effect on the fitted normal distribution. Gothenburg-Alingsås have the highest average standard distribution of all sections, and there are multiple curves in both directions. Skövde-Töreboda and Laxå-Hallsberg have the lowest average standard deviation, and both are track sections with a low number of significant curves. The differences between leading and trailing measurements are also important. They differ significantly, especially considering that trailing measurements give an increase in cycles with a lower stress than the quasi-static mean.

When comparing the onboard measurements to track quality data, it is clear that the onboard measurements have a natural scatter. This highlights the issue of storing onboard measurements in a cumulative matrix. Storage wise, it is a very efficient method, requiring only one matrix that does not change in size. However, this creates the issue of being unable to exactly link how different factors affect the data. Without a full time history of the data it is difficult to accurately determine the reasons for the scatter in the measurements. Looking at the correlation analysis, it is clear that different sections of track should not be compared when the data is stored in a cumulative matrix since track characteristics dominate over track quality in the onboard measurements. A section of track with a high number of curves can have a high QS-ratio, and a very straight section of track can have a low QS-ratio, which can lead to misleading results if the two are directly compared.

Moving on to the result of the correlation analysis, it is clear that no strong correlation can be seen. Starting with the combined analysis, the measurements for the leading position showed a correlation opposite to what was expected, with an increase in standard deviation when track quality increased. One reason for why this might be is that the measurements with the highest track quality are from the section Gothenburg-Alingsås in the southern direction, the section with the highest average standard deviation. Seemingly, other effects such as curves and switches dominate over the effect of track quality. The measurements from when the wheelset was trailing show a possible negative correlation, which is the expected result. However, this should not be accepted as a true correlation between track quality and onboard measurements for the same reasons presented for the leading position. Here, the measurements from Gothenburg-Alingsås in the northern direction have the lowest track quality out of all sections, while also having the highest standard deviation. This would indicate that lower track quality gives a higher standard deviation, but it is instead a result of a high number of curves and switches.

Looking at the track section specific analysis, only three track sections show a strong negative correlation, while another two have a weak negative correlation. Gothenburg-Alingsås with the wheelset in the leading position, Herrljunga-Skövde in the trailing position and Skövde-Töreboda in the trailing position all have strong negative correlations. The sections Gothenburg-Alingsås with the wheelset in the trailing position and Skövde-Töreboda in the leading position have weak negative correlations. These measurements might indicate that the expected correlation exists, however this is countered by the fact that four track sections show a weak positive correlation, and that three track sections show no correlation at all. No track sections show a strong positive correlation. Moreover, the sample sizes of the track specific analysis are very small, leading to an increased uncertainty regarding the results. Thus, while a negative correlation might exist, which should make it feasible to identify track quality through onboard measurements, the number of sections showing contradicting results are enough to not being able to draw any conclusions.

The selective analysis of Skövde-Töreboda was performed as a test case before the difference in leading and trailing positions was discovered. Since the section has a low number of switches and almost no curves, the section was used in a trial stage to establish the methods used. The arguments for the validity of this comparison is that the truncation of the normal distribution is the same for both the leading and trailing positions, meaning that the same data will be included. Furthermore, since the track is straight with other factors minimized, the stress spectra should be very close to representing the quasi-static loading of the wheelset. However, a small increase in loads below the quasi-static mean do exist, which might indicate that the stress spectra are different and should be kept separate. Looking at the correlation analysis, it indicates that a possible negative correlation do exist, however it can not be considered strong and a significant scatter does still exist. This can only be used as an indication that the expected correlation might exist, but further research is needed to verify this.

Finally, as was discussed in section 6.1, it is possible to use more refined methods to explore a possible correlation. However, since no results showed a strong indication of the expected correlation, the use of more refined methods was not explored further. Instead, focus was shifted to examine why the result of the study ended up as it did, and to what effect the limitations affected the result, further discussed in section 6.3.

6.3 Limitations

This study has struggled with different limitations affecting the results, as stated in each chapter. To begin with, the data accuracy can be questioned since the onboard measurements are stored in increments of 2.75 MPa. The observed increase in the mean of the fitted normal distributions is often in the range of one increment increase or decrease. This poses the question of to what extent does the stress increments of 2.75 MPa affect the results. Moreover, the observed variation between channels introduces an uncertainty since the measured stresses should be close to equal. Factors such as wheel out-of-roundness or worn out wheel profiles might affect measurements between channels, but the spread is quite significant for some runs. Since no pattern could be established, for example a permanent increase of 1 MPa for channel 4, a wrongly calibrated strain gauge should not be the issue. Thus, small differences between runs on the same track could possibly be linked to the nature of the measurement system. Combined with the limited amount of track measurements, there is room for different sources of errors in the results.

Furthermore, the most significant challenge has been the low sample size of runs. As described in section 4.7, if only 6% of measurements are usable for this purpose, it is hard to form specific conclusions based on the measurements. With more runs, it would have been possible to determine the natural scatter in the data by looking at the difference between runs that are close to each other in time. This could have been used to filter out other effects when forming a correlation between track quality and onboard measurements. Instead, the results show a significant scatter without a possibility to connect them to specific factors. Moreover, the small sample size leads to unreliable results from the track specific correlation analysis. In the current state, the analysis is susceptible to deviating measurements that could be from pure coincidence. A larger sample size would strengthen any conclusions based on the track specific analysis, and would make it possible to either accept or reject the hypothesis of a possible correlation. With the current state of the data, this is not possible.

7

Conclusions and future recommendations

Based on the results of the study with the limitations kept in mind, the following conclusions can be formulated:

- A correlation between track quality and onboard measurements cannot be established, however some results do indicate that such a correlation exist.
- With a cumulative data matrix, track characteristics dominate over track quality in the onboard measurement data.
- Track quality assessment with a cumulative matrix storage is dependent on the onboard measurement system uploading the data correctly, thus correctly indicating start and end point of the data
- The suitability of cumulative data storage should be questioned for track quality assessment.

This is not to say that the system is unsuitable for track quality assessment, but it is clear that many factors have to be taken into consideration to accurately interpret the measurements. Thus, future work should further investigate a possible correlation between track quality and onboard measurements with consideration to the mentioned conclusions, and also investigate to what extent other factors such as different track characteristics affect the onboard measurements. If possible, the effects of outside factors should be quantified and a way of filtering out these effects should be developed. This would lead to easier and more accurate assessments of track quality.

Bibliography

[1] M. Ben-Daya, U. Kumar, and D. P. Murthy, “Condition-based maintenance,” in *Introduction to Maintenance Engineering*. John Wiley & Sons, Ltd, 2016, ch. 16, pp. 355–387, ISBN: 9781118926581. DOI: `https://doi.org/10.1002/9781118926581.ch16`.

[2] P. Gullers, L. Andersson, and R. Lundén, “High-frequency vertical wheel–rail contact forces—field measurements and influence of track irregularities,” *Wear*, vol. 265, no. 9, pp. 1472–1478, 2008, Contact Mechanics and Wear of Rail/Wheel Systems - CM2006, ISSN: 0043-1648. DOI: `https://doi.org/10.1016/j.wear.2008.02.035`.

[3] S. Cantini, S. Cervello, and D. Regazzi, “Optimization of in-service ut inspections intervals based on wheelset loads moni-toring–smartset®,” in *Proceedings of the 2nd International Railway Symposium Aachen*, 2019, p. 332.

[4] M. Maglio, T. Vernersson, J. C. O. Nielsen, *et al.*, “Railway wheel tread damage and axle bending stress – instrumented wheelset measurements and numerical simulations,” *International Journal of Rail Transportation*, vol. 10, no. 3, pp. 275–297, 2022. DOI: `10.1080/23248378.2021.1932621`.

[5] M. Maglio, E. Kabo, and A. Ekberg, “Railway wheelset fatigue life estimation based on field tests,” *Fatigue & Fracture of Engineering Materials & Structures*, vol. 45, no. 9, pp. 2443–2456, 2022. DOI: `https://doi.org/10.1111/ffe.13756`.

[6] M. Maglio, E. Kabo, and A. Ekberg, “Relating the influence of track properties to axle load spectra through onboard measurements,” *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 238, no. 1, pp. 3–13, 2024. DOI: `10.1177/09544097231170086`.

[7] Trafikverket. “Baninformation (bis).” In Swedish. (2018), [Online]. Available: `https://bransch.trafikverket.se/tjanster/system-och-verktyg/forvaltning-och-underhall/BIS---Baninformation/` (Accessed on 21.5.2025).

[8] Trafikverket. “Optram.” In Swedish. (2024), [Online]. Available: `https://bransch.trafikverket.se/tjanster/system-och-verktyg/forvaltning-och-underhall/Optram/` (Accessed on 21.5.2025).

[9] E. Bernal, M. Spiryagin, and C. Cole, “Onboard condition monitoring sensors, systems and techniques for freight railway vehicles: A review,” *IEEE Sensors Journal*, vol. 19, no. 1, pp. 4–24, 2019. DOI: `10.1109/JSEN.2018.2875160`.

[10] E. Fumeo, L. Oneto, and D. Anguita, “Condition based maintenance in railway transportation systems based on big data streaming analysis,” *Procedia*

Computer Science, vol. 53, pp. 437–446, 2015, INNS Conference on Big Data 2015 Program San Francisco, CA, USA 8-10 August 2015, ISSN: 1877-0509. DOI: `https://doi.org/10.1016/j.procs.2015.07.321`.

[11] A. Peinado Gonzalo, R. Horridge, H. Steele, E. Stewart, and M. Entezami, "Review of data analytics for condition monitoring of railway track geometry," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 12, pp. 22 737–22 754, 2022. DOI: `10.1109/TITS.2022.3214121`.

[12] A. Ekberg and E. Kabo, "Key parameters and requirements for track health monitoring and prediction," Chalmers, Tech. Rep., 2022.

[13] A. M. Remennikov and S. Kaewunruen, "A review of loading conditions for railway track structures due to train and track vertical interaction," *Structural Control and Health Monitoring*, vol. 15, no. 2, pp. 207–234, 2008. DOI: `https://doi.org/10.1002/stc.227`.

[14] A. K. Sajjad Z. Meymand and M. Ahmadian, "A survey of wheel–rail contact models for rail vehicles," *Vehicle System Dynamics*, vol. 54, no. 3, pp. 386–428, 2016. DOI: `10.1080/00423114.2015.1137956`.

[15] Trafikverket, *Spårläge*, Trafikverkets infrastrukturregelverk, In Swedish, Apr. 1, 2020.

[16] A. G. Asuero, A. Sayago, and A. G. G. and, "The correlation coefficient: An overview," *Critical Reviews in Analytical Chemistry*, vol. 36, no. 1, pp. 41–59, 2006. DOI: `10.1080/10408340500526766`.

[17] D. Freedman, R. Pisani, and R. Purves, *Statistics: Fourth International Student Edition* (Emersion: Emergent Village Resources for Communities of Faith Series). W.W. Norton & Company, 2007, ISBN: 9780393930436.

[18] Trafikverket. "Västra stambanan." In Swedish. (2022), [Online]. Available: `https://www.trafikverket.se/resa-och-trafik/jarnvag/sveriges-jarnvagsnat/vastra-stambanan/` (Accessed on 21.5.2025).

[19] SJ. "Våra tåg." In Swedish. (2024), [Online]. Available: `https://www.sj.se/allt-om-resan/vara-tag` (Accessed on 21.5.2025).

[20] M. Hildingsson, S. Barthelemy, A. Westling, J. Spännar, J. Hjort, and L. Leppänen, *Datadokumentation och inställningsfiler i optram*, In Swedish, Trafikverket, 2025.

[21] A. Ryabov, *Fitting a truncated normal (gaussian) distribution*, `https://www.mathworks.com/matlabcentral/fileexchange/64040-fitting-a-truncated-normal-gaussian-distribution`, MATLAB Central File Exchange, 2025.

[22] OpenStreetMap contributors, *Planet dump retrieved from https://www.openrailwaymap.org/*, `https://www.openrailwaymap.org/`, 2017.

A

Track section overview

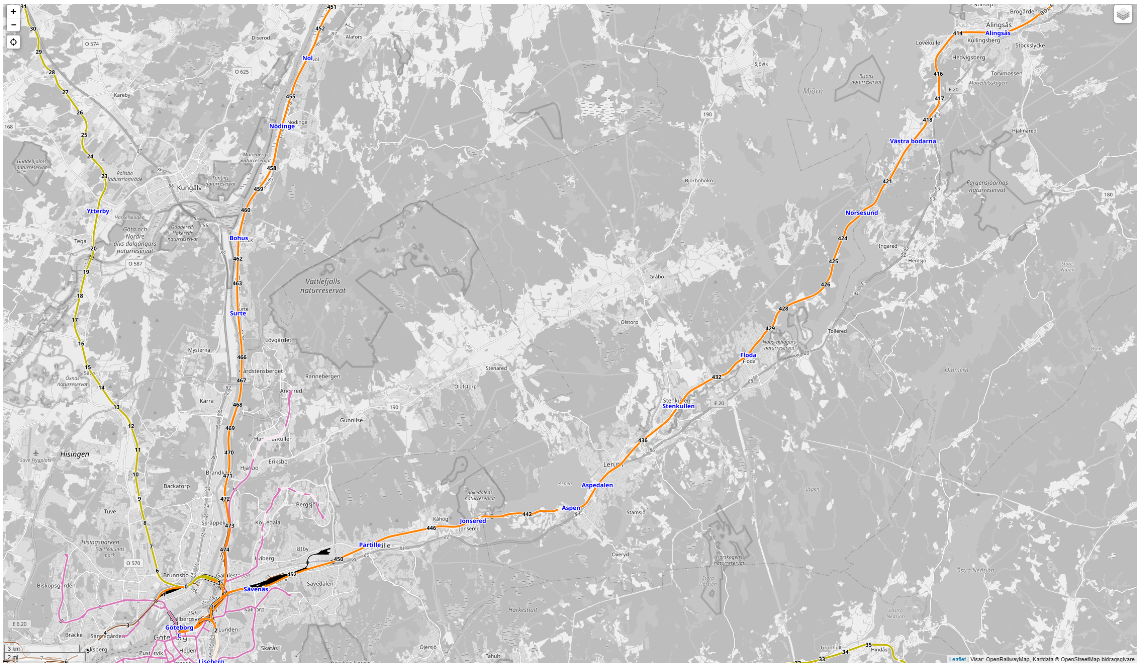


Figure A.1: Overview of Gothenburg-Alingsås, map created by OpenRailwayMap [22]

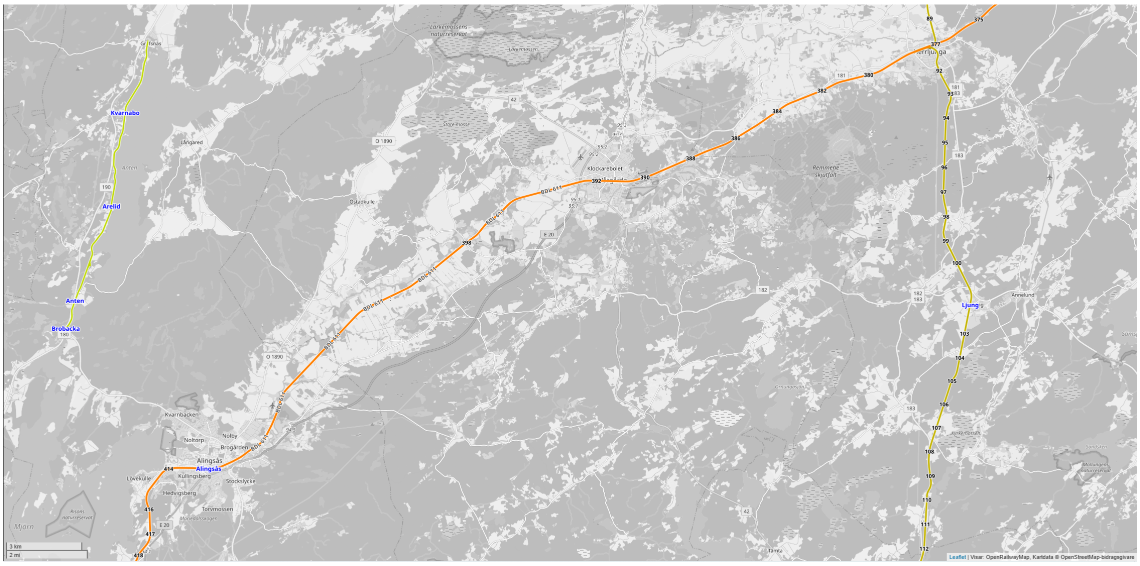


Figure A.2: Overview of Alingsås-Herrljunga, map created by OpenRailwayMap [22]

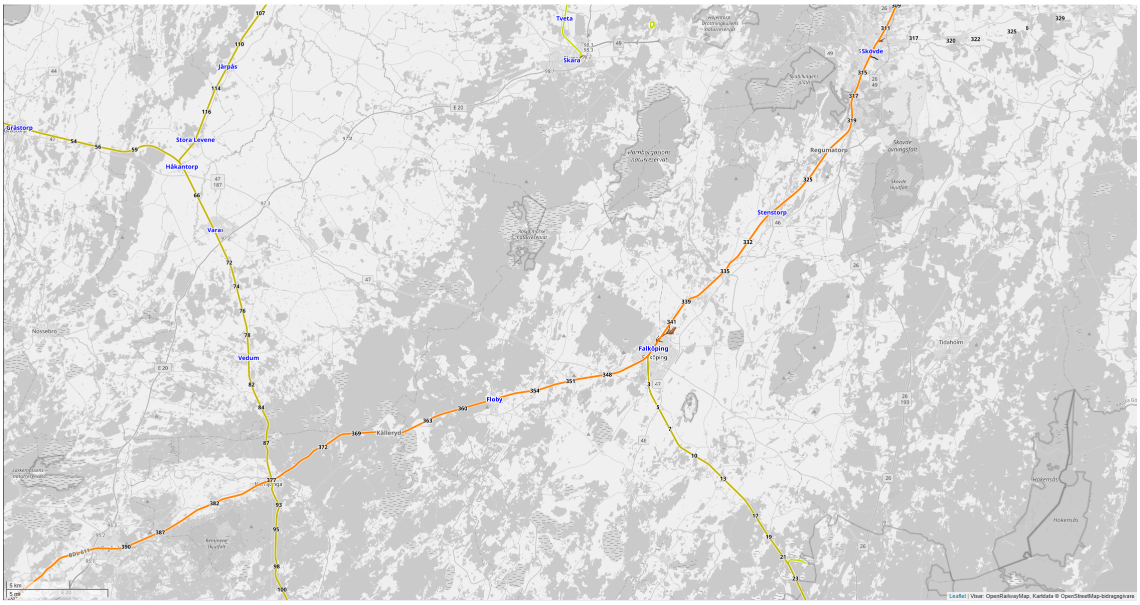


Figure A.3: Overview of Herrljunga-Skövde, map created by OpenRailwayMap [22]

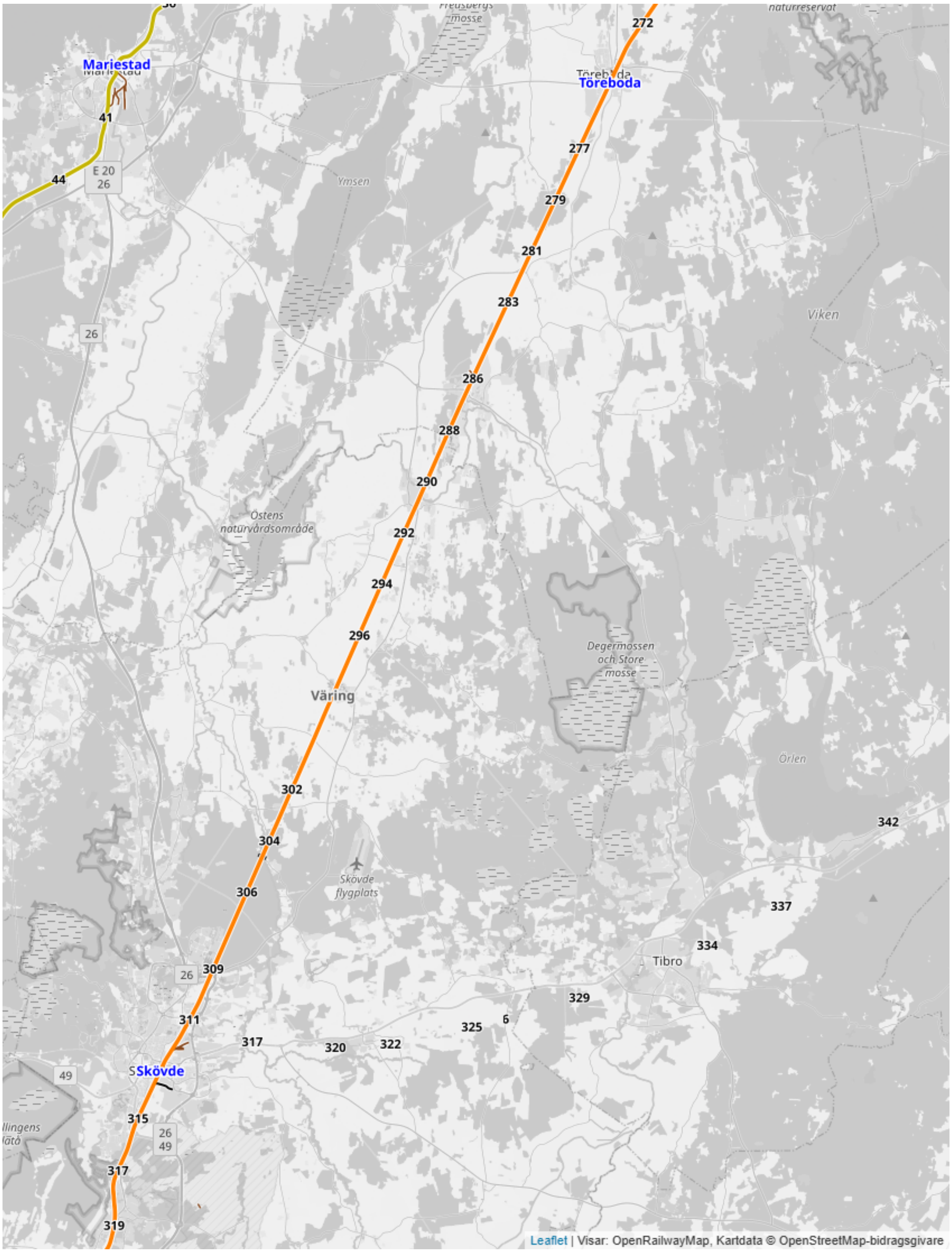


Figure A.4: Overview of Skövde-Töreboda, map created by OpenRailwayMap [22]

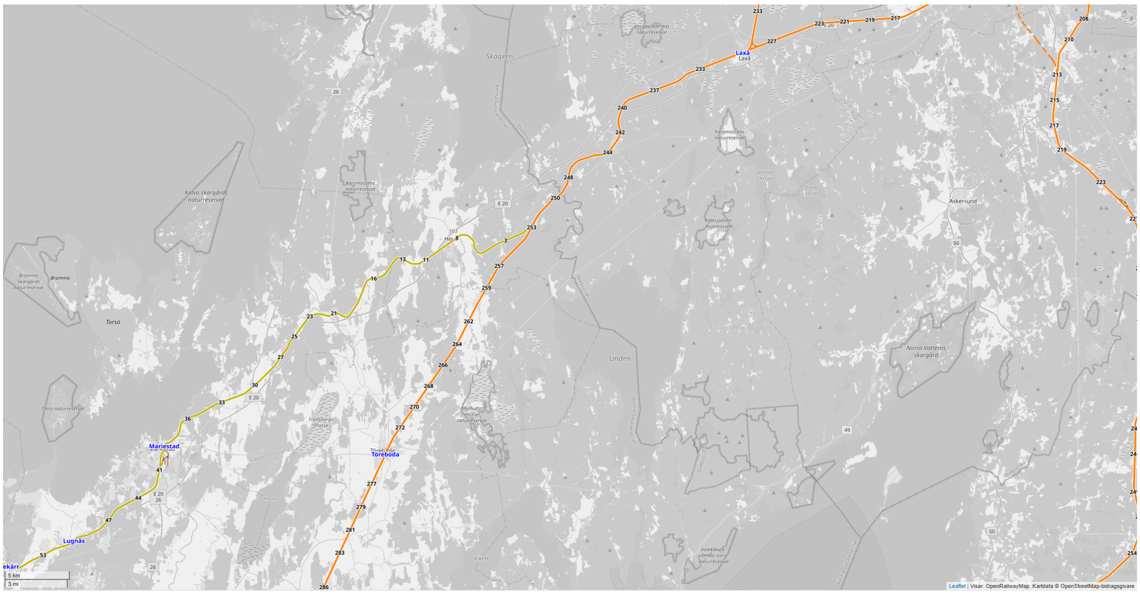


Figure A.5: Overview of Töreboda-Laxå, map created by OpenRailwayMap [22]

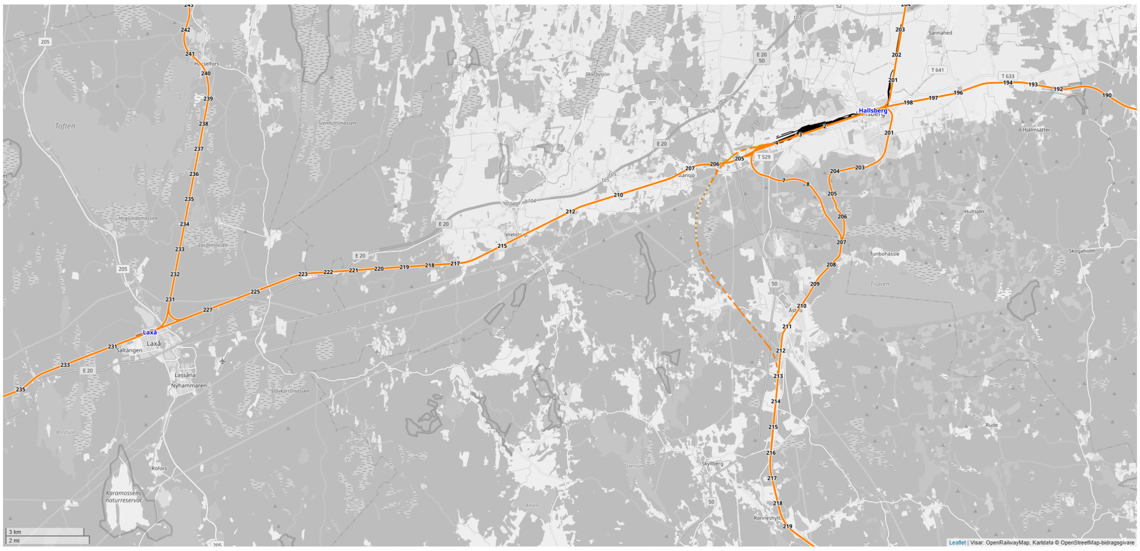


Figure A.6: Overview of Laxå-Hallsberg, map created by OpenRailwayMap [22]

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